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UNMANNED EVALUATION OF SELECT COMMERCIALLY AVAILABLE OPEN CIRCUIT SCUBA REGULATORS FOR COLD WATER DIVING

NAVY EXPERIMENTAL DIVING UNIT

Author: V. Ferris

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19. ABSTRACT: This report summarizes the results for five preselected commercially available open circuit scuba regulator models that were tested to determine their suitability for U. S. Navy diving. Five units of each model regulator were tested in both cold (38 °F) and freezing (29 °F) water. To emulate the ventilation of a diver, a breathing simulator with a sinusoidal breathing pattern was used, and the exhaled gas was heated and humidified. Freeze-up testing was conducted in freezing water, at a ventilation rate of 62.5 liters per minute (L/min) to a depth of 198 feet of seawater (fsw). To assess the resistive effort at various ventilation rate and volume combinations ranging from 22.5 to 90 L/min, resistive effort tests were performed in cold water from the surface to 198 fsw, with stops made every 33 fsw,. Two regulator models are recommended for use in freezing water.

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INTRODUCTION

The Navy Experimental Diving Unit (NEDU) has tested commercially available open circuit scuba regulators under the direction of several Naval Sea Systems Command (NAVSEA) tasking efforts.[1–4] NEDU has also been tasked to test and evaluate current production models of several commercially available open circuit scuba regulators of interest to the Navy, to determine which ones may meet the Navy's current performance criteria for cold water diving. [5–7] This test series differs from previous tasking in that the tested regulators were limited to those of the greatest interest to the Navy for cold water diving use, with *cold water diving* being defined as that in conditions where a regulator can freeze up — conditions considered to be greater than or equal to 29 °F but less than 38 °F. The regulators tested were purchased from local equipment suppliers. After testing was completed, the test samples were retained at NEDU.

A test plan was developed to describe the unmanned test procedures to which each candidate regulator was to be subjected.[8] The performance criteria for each regulator was its ability to provide sufficient breathing air and to avoid sustained free flow in a cold water environment. No manned testing was authorized in connection with this specific task.

For statistical purposes, five regulators of each model were tested. Selection of the candidate regulator manufacturers and models was based on several factors: in part, on current listing on the *Authorized for Navy Use* (ANU) list, past regulator performance from manned testing in Antarctica, or current inventory in fleet diving units but untested by NEDU.[1–4, 9, 10]

The Poseidon Xstream Dive model, currently on the ANU list for cold water use, is no longer being manufactured. Therefore, the Poseidon Xstream Deep Mk3 model, being a currently available regulator, was selected for testing. Five Poseidon Xstream Deep Mk3 model regulators with side-mounted first-stages were purchased from local equipment suppliers and tested.

The Mares Proton Metal V32 model has not been tested by NEDU and is not currently on the ANU list. Since it is currently in fleet inventory, it was initially selected for testing. But before testing began, this regulator was determined to no longer be in production, and since very few remain in fleet inventory, this model was not tested.

The Mares Proton Ice V32 Teflon® with a cold water kit installed, was previously tested by NEDU and rated as being acceptable for temperatures greater than or equal to 29 °F with minor freeze-up risk.[2] Since being tested by NEDU, this model had been modified to some degree by the manufacturer and renamed the "Proton Ice Extreme V32" with cold water kit installed. This new commercially available model was currently replacing fleet inventory of the Proton Ice Teflon® but was untested by NEDU. In addition to having been untested by NEDU, the Proton Ice Extreme regulator model has exhibited unfavorable results such as sustained free-flow conditions during manned dive testing in

Antarctica.[10, 11] Therefore, it was decided to include this model in the protocol, and five test units of the Proton Ice Extreme V32 were obtained for testing from existing fleet inventory.

Upon inspection of these regulators, NEDU determined that during periodic overhauls in the fleet, each of these regulators had had its cold water kit (consisting of the diaphragm and silicone oil) removed from the first-stage assembly. NEDU had not tested the Mares Proton Ice Teflon® regulators in this configuration, since this was a regulator modification unacceptable to the manufacturer's design for cold water usage. These test units were therefore not tested and were returned to fleet inventory with a note that they were not approved for use. Instead, five new Proton Ice Extreme V32 models, with their cold water assembly in place, were purchased from local equipment suppliers for testing. Since this Mares Proton Ice Extreme model regulator was widely distributed throughout the fleet, NEDU also decided to subject it to additional tests for its warm water suitability, in case it did not pass the cold water tests.

NEDU had tested earlier versions of the Sherwood Blizzard and Maximus regulator models, but these were not currently on the ANU list.[12] Since new versions of the models were commercially available and are popular among divers in the cold waters of Antarctica, these newer versions were selected for testing.[9] The Sherwood regulators tested were purchased from local equipment suppliers.

After the test plan was executed and before this report was generated, Mares funded NEDU to subject five test units of their Abyss Extreme model regulator — consisting of the MR22T first-stage and Abyss second-stage with integrated intermediate pressure hose — to the testing protocol. Mares provided the Abyss test units directly to NEDU. During Phase 2 testing, as presented in the **RESULTS** section, the Abyss units exhibited extreme intermediate pressure undulations well outside the manufacturer's limits, and testing was terminated. After this testing was terminated, NEDU and Mares personnel conducted technical meetings[13], and these resulted in suggestions to mate the Mares Proton Ice Extreme V32 first-stage assembly with a Mares Abyss second-stage assembly and its integrated intermediate pressure hose — and to subject these modified regulators to the testing protocol. The test results from these modified regulators are included in this report.

With the test plan successfully executed, NEDU submitted preliminary results and conclusions for the Mares Proton Ice Extreme V32 and Poseidon Xstream Deep Mk3 models in a technical letter.[14] Included herein are detailed results, analyses, and comparisons to established performance goals and limits, conclusions, and recommendations regarding the regulators tested.

METHODS

GENERAL

The methods used in the evaluation were as described in NEDU test plan, NEDU TP 09-24[8] and is based on parameters set forth in NEDU Technical Manual 01-94.[6] All unmanned testing was conducted at the NEDU Experimental Diving Facility (EDF) “Alpha” chamber, with “Bravo” chamber as an alternate. Unless otherwise noted, manning and test protocols follow standard operating procedures.[6,8]

NEDU acquired five units of each of several commercial off-the-shelf (COTS) regulator models from various manufacturers. This sample size (n = 5) yields adequate statistical reliability and is typical for NEDU’s evaluations of equipment for U.S. Navy certification.[1–4, 6] All units were set up following normal operating procedures, except as noted in each phase of testing. Before testing, NEDU documented any minor modifications made to the underwater breathing apparatus (UBAs) for testing purposes in the EDF: such modifications included, but were not limited to, removing mouthpieces, adding adaptors for pressure sensing and interfacing with routing blocks, and adjusting to intermediate pressures (IPs).

All regulators were tested in the upright position, simulating a diver standing or swimming upright. All regulators were subjected to a hierarchical series of unmanned tests consisting of the three sequential phases presented in the **PERFORMANCE GOALS** section.

PERFORMANCE GOALS

Phase 1:

<u>Visual inspection and dry bench testing (surface)</u>

The intermediate pressure IP — measured with supply pressures of 500 psi, 1500 psi, and 3000 psi — and the breathing effort required to initiate flow (negative or “cracking” pressure) were checked to verify that they were within the manufacturers’ recommended ranges. If the over-bottom pressure of a tested regulator had been outside the specified range, adjustments would have been made to try to effect compliance before Phase 2 testing began. No regulator adjustments were required.

Phase 2:

<u>Freeze-up testing</u>

A low-compliance, computer-controlled breathing machine (Reimers Systems, Inc.; Lorton, VA) was used to simulate the ventilation process of a diver at a respiratory minute volume (RMV) of 62.5 L/min, which is considered a “heavy” workload. Saline water in a range of 35–40 parts per thousands (ppt) of salt and a temperature range of 29 ± 1 °F (–1.7 ± 0.6 °C) were maintained to simulate the ocean environment. Real-time

video monitors were used to visually determine the possible development of a regulator "freeze up" indicated by a sustained flow of bubbles from the exhaust port. At various time intervals, the over-bottom pressure and resistive effort (analysis of pressure and volume [PV] variables) were monitored and recorded.

Phase 3:

Cold water resistive effort testing

The resistive effort performance goal has been established for RMVs up to 62.5 L/min and depths to 198 fsw at supply pressures of 1500 psi. For cold water resistive effort testing, a regulator's breathing performance is considered to be acceptable if the mean resistive effort during testing is no greater than 1.37 kPa.[6] Furthermore, resistive effort performance limits of 1.53 kPa, have been established for the same RMVs, depth and supply pressures.[7] As used in Phase 2, the breathing machine simulated the ventilation of a diver at various RMVs. Saline water in the range of 35–40 ppt and a temperature range of 38 ± 1 °F (3.3 ± 0.6 °C) were maintained to simulate the ocean environment. The resistive effort (analysis of PV variables) were monitored and recorded for various depth and breathing rate combinations. After this phase was completed, the test articles were reevaluated on the test platform used in Phase 1 to determine whether the intermediate pressure, at the three different supply pressures, had been affected during Phases 2 or 3. These results were logged and included as part of the Phase 1 documentation.

TERMINATION CRITERIA

Termination criteria for both individual test items and the regulator makes and models were established for each phase of testing.

Individual Regulator Bench Test or Dive Termination

Any regulator test unit not meeting all criteria within each phase was said to have ***failed*** that phase; otherwise, the individual test unit ***passed***.

Phase 1 Criteria:

- Inability to set or maintain manufacturer-specified IP
- Sustained free flow or failure to deliver gas
- Any event for which the EDF test supervisor directed termination

Phase 2 Criteria:

- Inhalation or exhalation pressure exceeding 7 kPa
- Sustained free flow or failure to deliver gas
- Any event for which the EDF test supervisor directed termination

Phase 3 Criteria:

- Inhalation or exhalation pressure exceeding 7 kPa at a specific RMV and depth, a level that terminated only that set of test conditions. The remaining test battery was attempted.
- Sustained free flow or failure to deliver gas.
- Any event for which the EDF test supervisor directed termination

Make and Model Termination

Phase 1 Criteria:

- If two of the five regulators of any make and model failed the Phase 1 bench test, further testing of that make and model was terminated, and that regulator model was excluded from Phase 2 tests. All regulator models had their IPs checked after all tests were completed.

Phase 2 Criteria:

- If a specific make and model had three failures, the cumulative failure rate was determined. If the cumulative failure rate was greater than 33%, testing of all regulators of that make and model was terminated and those regulators were excluded from Phase 3 tests. Otherwise, testing of that make and model continued, the cumulative failure rate was recalculated, and the termination criteria were reevaluated at the end of each dive.

Phase 3 Criteria:

- No failure criteria
- All five regulators of any make and model having successfully passed Phase 2 tests were subjected to resistive effort tests in Phase 3.

Operational and Safety Termination (All Phases)

Any test was terminated at the discretion of the test supervisor exercising any of his concerns, including those for

1. Safety of personnel
2. Damage to test equipment or the UBA
3. Failure of the test UBA

EXPERIMENTAL DESIGN AND ANALYSIS

The first phase of testing was conducted on a test platform designed for testing open circuit scuba regulators at atmospheric pressure. As part of this dry bench evaluation, the ability of each regulator to hold IP was determined and recorded. In addition, the cracking pressure was observed and recorded.

Phases 2 and 3 used the test configuration shown in Figure 1.

During Phases 2 and 3, the expired gas from the breathing machine was heated and humidified to maintain 100% water saturation at an appropriate temperature (dependent on the water temperature) at the mouthpiece of the UBA. The following equation was used to calculate the appropriate target for expired gas temperature:

$$T_{expired} = 24\ °C + 0.32T_{inspired},$$

where the temperatures $T_{expired}$ and $T_{inspired}$ are expressed in °C, and $T_{inspired}$ is defined to be equal to the surrounding water temperature.[15]

Due to the technique used to heat and humidify the expired gas, it was not possible to achieve the desired temperature for all water temperature and ventilation rate combinations at target depths. Any deviations from the stated expired gas temperature intervals in Phases 2 and 3 were recorded and are included in the **RESULTS** section of this report.

As outlined in the test plan, the following parameters were controlled, varied, or recorded for each phase of testing:

Testing supply pressure
Intermediate pressure
Test depth, salinity, and temperature
Breathing and testing medium of diver's breathing air
Breathing rate and tidal volume
Exhalation gas humidity and temperature
Resistive effort

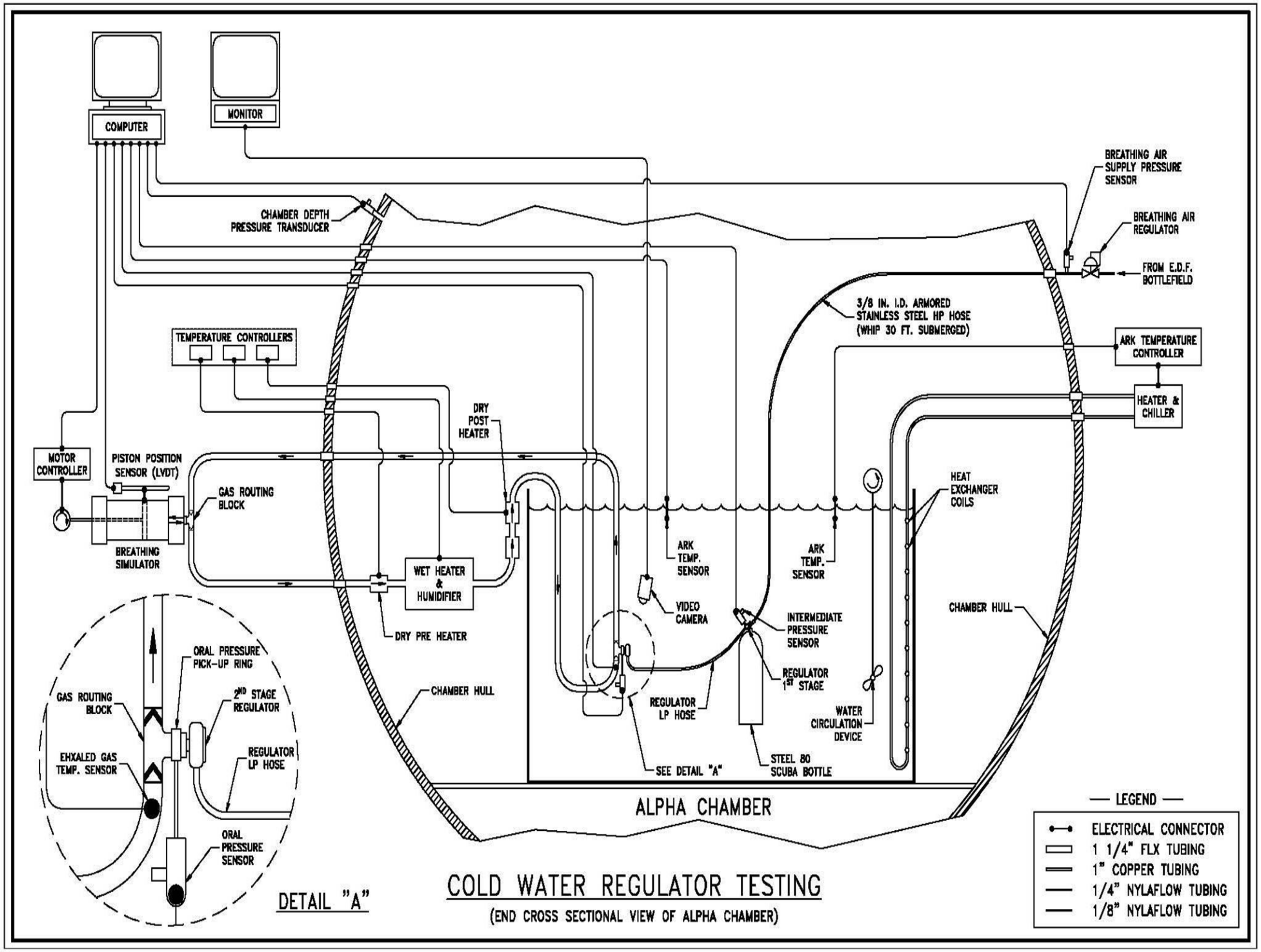

Figure 1. Chamber setup and instrumentation as used for unmanned regulator testing

TEST PROCEDURE

A description of the procedures used to conduct the tests is included in the test plan.[8]

RESULTS

Four commercially available regulator models and one combination regulator from three regulator manufacturers were selected as candidates for testing. The models tested were the Poseidon Xstream Deep Mk3 with side-mounted first stage, the Mares Proton Ice Extreme V32, the combination of the Mares Proton Ice Extreme V32 first stage and Abyss second stage, and the Sherwood Maximus and Blizzard. The configurations of each tested regulator model are listed in Appendix A — including photographs of each model as purchased, or in the case of the combination regulator, as assembled at NEDU. The NEDU tracking and manufacturer serial numbers of each test unit are listed in Appendix B. All regulators were tested upright, with a single second stage attached to the first stage via the standard length IP hose supplied by the manufacturer. The first stage was attached to the scuba tank manifold block with a yoke-style attachment provided by the manufacturer. No other IP devices (i.e., inflation whip or second-stage octopus), submersible pressure gauge (SPG), or gas-integrated computer were connected to the first stage. An IP sensor transducer was attached to the first stage of each test unit for all phases. At completion of testing, all units were returned to their *as received* configuration. Test results for each regulator model following each phase are listed in Appendix C and explained in the current section.

All five regulator models passed Phase 1 of the study and advanced to Phase 2 testing. The Poseidon Xstream Deep Mk3 units did not exhibit freeze-up conditions at 29 °F and were advanced to Phase 3 tests. Both Sherwood models and the Mares Proton Ice Extreme V32 model exhibited freeze-ups during Phase 2 testing at a depth of 198 fsw in water temperatures at or near 29 °F. Having been terminated in Phase 2 tests at 198 fsw and 29 °F, the Mares Proton Ice Extreme V32 was tested for freeze-up at a depth of 132 fsw and 29 °F, as specified in the protocol, and it was again terminated due to sustained free flows. The Mares Proton Ice Extreme V32 units were finally tested at 198 fsw and 38 °F, as dictated in the protocol, and, when they did not exhibit freeze-up, were advanced to Phase 3 tests.

NEDU performed independently conducted, unmanned cold water tests on the Mares Abyss model regulator under the same protocol. Five units of the Mares Abyss Extreme regulator with an MR22T first-stage assembly were tested as supplied by the manufacturer.

Due to severe IP undulations in excess of the manufacturer-recommended operating limits, Phase 2 testing was terminated for each. These elective terminations were initiated before any onset of possible second-stage freeze-up conditions could be determined. Since the second stage of the Abyss regulator and integrated IP hose had not shown freeze-ups before those Phase 2 terminations, a motive for testing them subsequently remained. The five test units of the Abyss second stage and their

integrated IP hoses were thus connected to the Proton Ice Extreme V32 first stages after the latter's standard second stage and hose had been removed. This combination did not freeze up at 29 °F and was advanced to Phase 3 tests.

Having been terminated in Phase 2 testing, the Sherwood models were not advanced to Phase 3 tests. Although the Mares Proton Ice Extreme was terminated in Phase 2 tests at 29 °F, it was advanced to Phase 2 tests at 38 °F — at which it performed satisfactorily — and was then advanced to Phase 3 tests. Coupled with the Abyss second stage, the Mares Proton Ice Extreme first stage was advanced to Phase 3 tests. All three regulator models advancing to Phase 3 tests performed satisfactorily during this final phase.

All regulator models underwent Phase 1 exit criteria for postdive logging of IPs at various supply pressures for comparison to predive values. All individual test units returned to nominal Phase 1 intermediate pressure after cold water exposure.

Figures 2–10 were created from raw data collected during Phase 3 (38 °F) testing. Of these, Figures 2–7 provide scatterplots of the descriptive statistics for the sample arithmetic mean of the resistive effort (used as a measure of central tendency) and the sample standard deviation of the data from that arithmetic mean (used as a measure of dispersion) for all five units of each model advancing to Phase 3 tests. These Figures 2–7 (with two plots for each of the five test models) indicate the relationship between the resistive effort and the ventilation rate (Figures 2, 4, and 6) or the depth (Figures 3, 5, and 7) for the regulators tested in Phase 3. On any plot for a specified depth, arithmetic mean points that lack standard deviation whiskers indicate that only a single data value was available for the arithmetic mean calculation: the other data values exceeded the oronasal pressure limits of 7 kPa, as set forth in the protocol at that depth and ventilation rate. It is understood that these scatterplots are for discrete values of the arithmetic mean and associated sample standard deviations of the data set for each model. Lines connecting arithmetic mean values at various ventilation rates for a given depth indicate only a trend and do not indicate actual data values or calculations.

For a test article randomly selected from each model that had advanced to Phase 3, Figures 8–10 provide a representative of the pressure-volume relationship in a breathing loop cycle for a single 198 fsw dive at a 62.5 L/min ventilation rate. These figures display 10 loop cycle iterations, with the ensemble average loop overlaid. These figures indicate a very low overall resistive effort throughout the breathing cycle at the depth of 198 fsw. Nearly all of the resistive effort is experienced during the exhalation phase of the breathing cycle. During the inhalation phase of the breathing cycle, the resistive effort is nearly zero and the regulator can actually provide a positive pressure where the breathing medium actively flows into the diver's mouth.

The resistive effort performance of regulators tested in Phase 3 was also compared to those performance goals and limits that NEDU has established for UBAs.[6,7] These resistive effort performance goals and limits for a self contained UBA (0–198 fsw, air as breathing media, and open circuit demand regulator) are defined as not to exceed 1.37

kPa (performance goal) and 1.53 kPa (performance limit) for ventilation rates of 22.5 L/min (*light* workrate), 40 L/min (*moderately heavy* workrate), and 62.5 L/min (*heavy* workrate) and for tidal volumes of 1.5, 2.0, and 2.5 liters, respectively. For each model regulator tested in Phase 3, all test units performed well within the performance goal and limit. Although the Phase 3 regulators were tested at ventilation rates of 75 L/min (*severe* workrate) and 90 L/min (*extreme* workrate), no performance goals are established for these ventilation rates.

The empirical data for these higher ventilation rates are included in Figures 2–7 to indicate how resistive effort at these rates tends to increase substantially from that of the lower three ventilation rates. These lower ventilation rates provide a longer effective dwell time between the super-cooled air inside the IP hose and the relatively warmer surrounding water temperature. This longer dwell time provides additional heat transfer and may reduce the incidence of ice-induced free flow. The IP hose and metal connections between the first- and second-stage assemblies of each model regulator in effect act as low-efficiency heat exchangers. While conducting Phase 2 tests on the Mares Abyss regulator, investigators noticed that the IP hose — which is less insulated than typical rubber hoses found on the other models tested — exhibited a buildup of slushy ice along the hose's entire outer surface. Therefore, any modifications to — or additions to or substitutions of — the intermediate pressure hose may affect the free-flow incidence rate.

Figures 11 and 12 indicate typical first-stage assembly icing during Phase 2 testing of the Mares Abyss and the Poseidon Xstream Deep Mk3 model units, respectively. Figure 13 indicates typical second-stage icing during Phase 2 testing of the Poseidon Xstream Deep Mk3 model units. Icing can be seen on both the external portion of the second-stage assembly — where the metal portion of the IP hose connects to that assembly — and the interior of that assembly, as viewed looking inward from the mouthpiece adaptor (shown in blue). All makes and models of test units exhibited some degree of both first- and second-stage assembly icing. This is a normal occurrence during both laboratory and field testing and therefore does not necessarily provide a useful indication for predicting the onset of second-stage assembly free flow.

Having been terminated for meeting both individual test unit and model termination criteria outlined in the test protocol, the Sherwood Maximus and Blizzard models and the Mares Proton Ice Extreme V32 units did not perform satisfactorily in the 29 °F water tests of Phase 2. During Phase 2, the Mares Proton Ice Extreme V32 units with cold water kits installed performed satisfactorily in 38 °F water tests, and they subsequently were advanced to, and performed satisfactorily in, Phase 3 tests. The Poseidon Xstream Deep Mk3 units did perform satisfactorily in Phase 2 tests and subsequently were advanced to Phase 3, where they also performed satisfactorily.

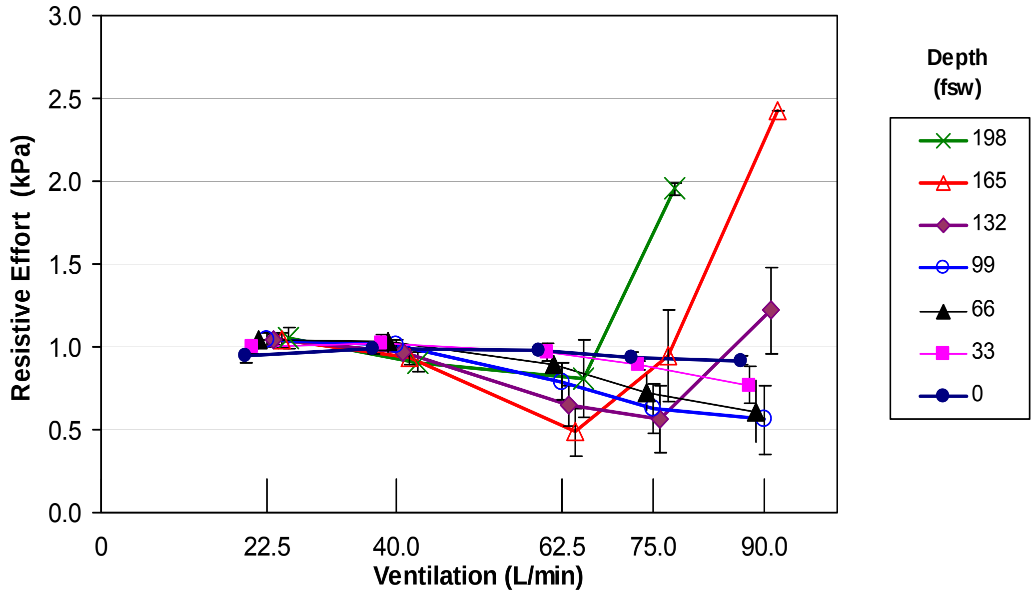

Figure 2. Resistive Effort vs Ventilation for the Mares Proton Ice Extreme V32 at 38 °F

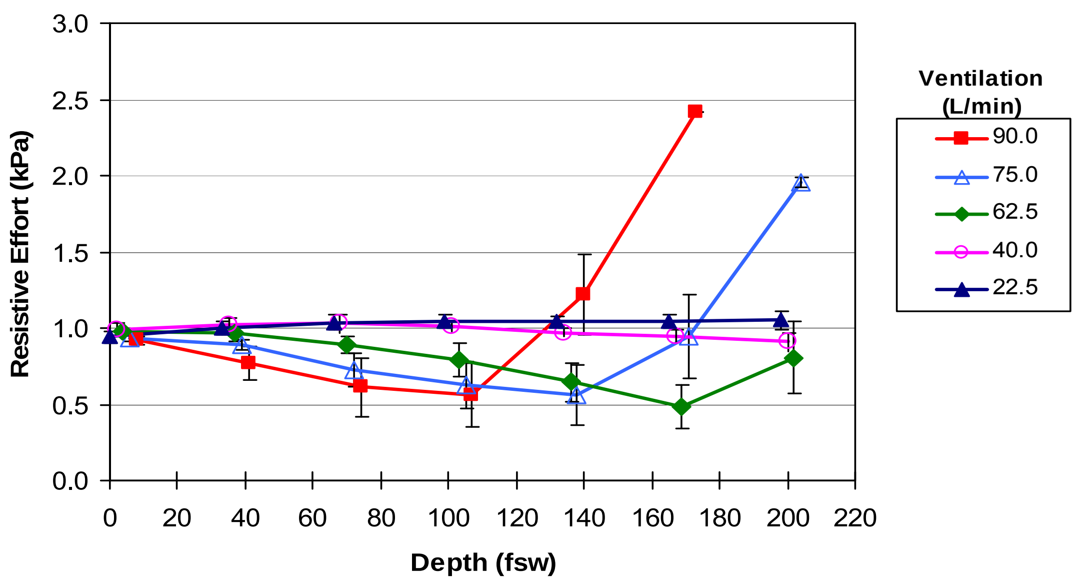

Figure 3. Resistive Effort vs Depth for the Mares Proton Ice Extreme V32 at 38 °F

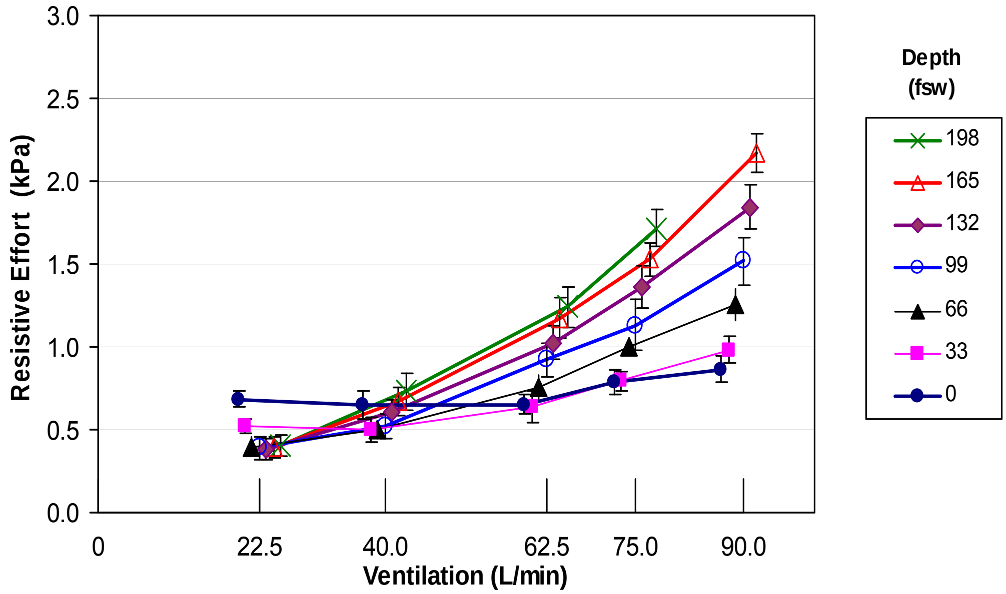

Figure 4. Resistive Effort vs Ventilation for the Poseidon Xstream Deep Mk3 at 38 °F

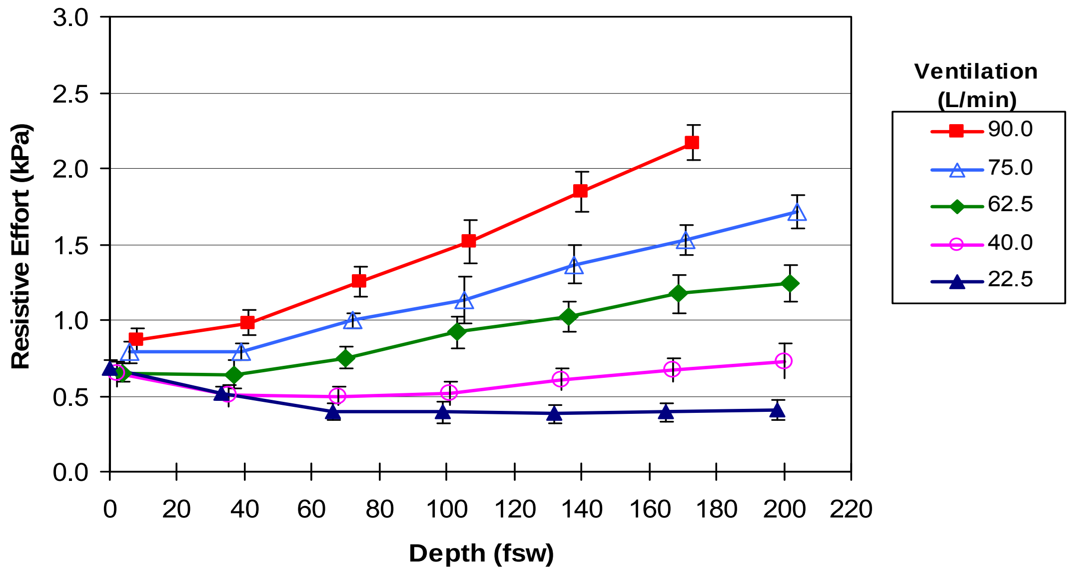

Figure 5. Resistive Effort vs Depth for the Poseidon Xstream Deep Mk3 at 38 °F

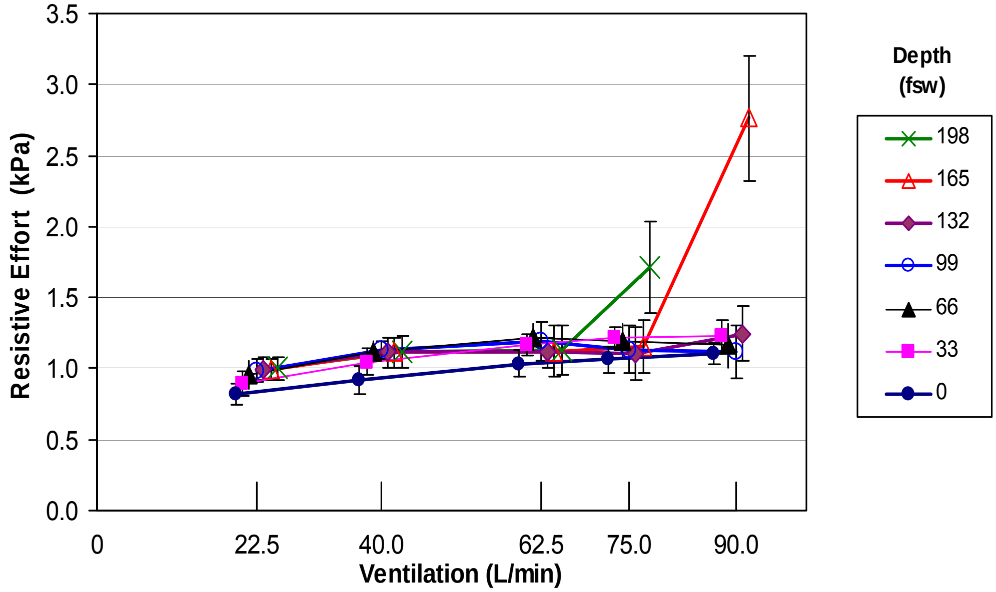

Figure 6. Resistive Effort vs Ventilation for the Mares Proton Ice Extreme V32 with Abyss Second Stage at 38 °F

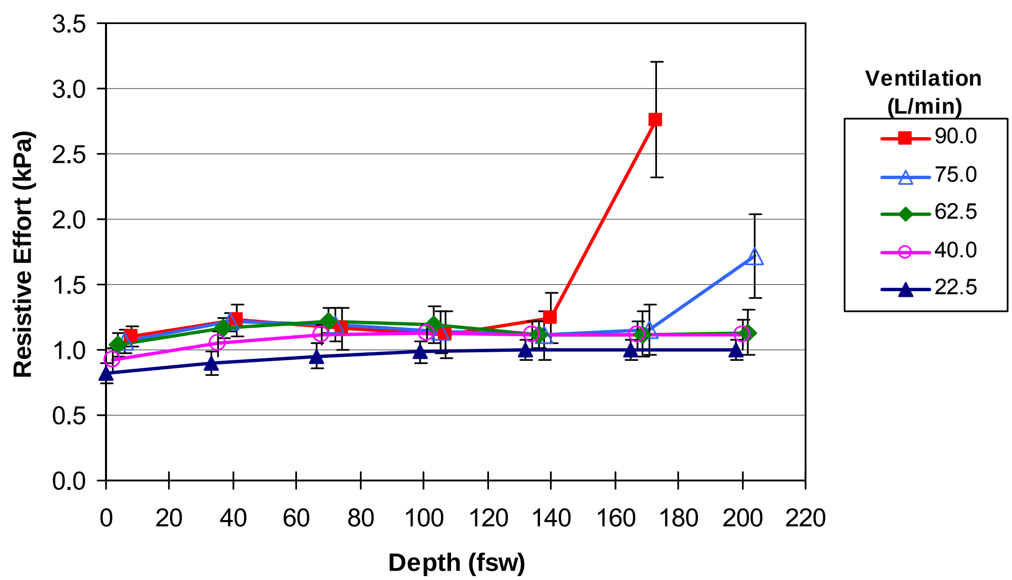

Figure 7. Resistive Effort vs Depth for the Mares Proton Ice Extreme V32 with Abyss Second Stage at 38 °F

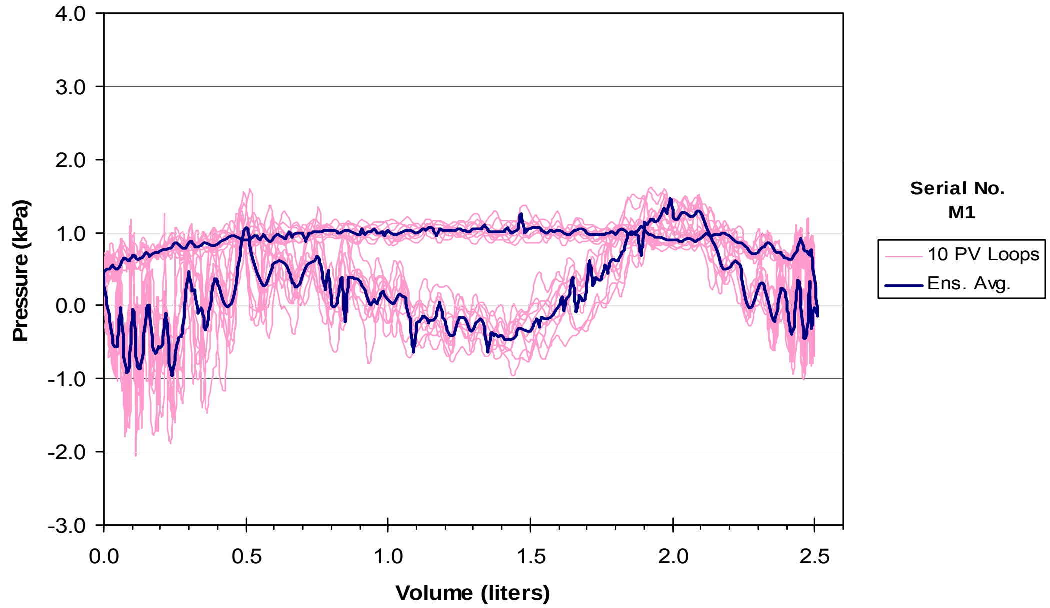

Figure 8. Pressure-Volume Loop for the Proton Ice Extreme V32 at RMV 62.5 L/min, 38 °F, and 198 fsw

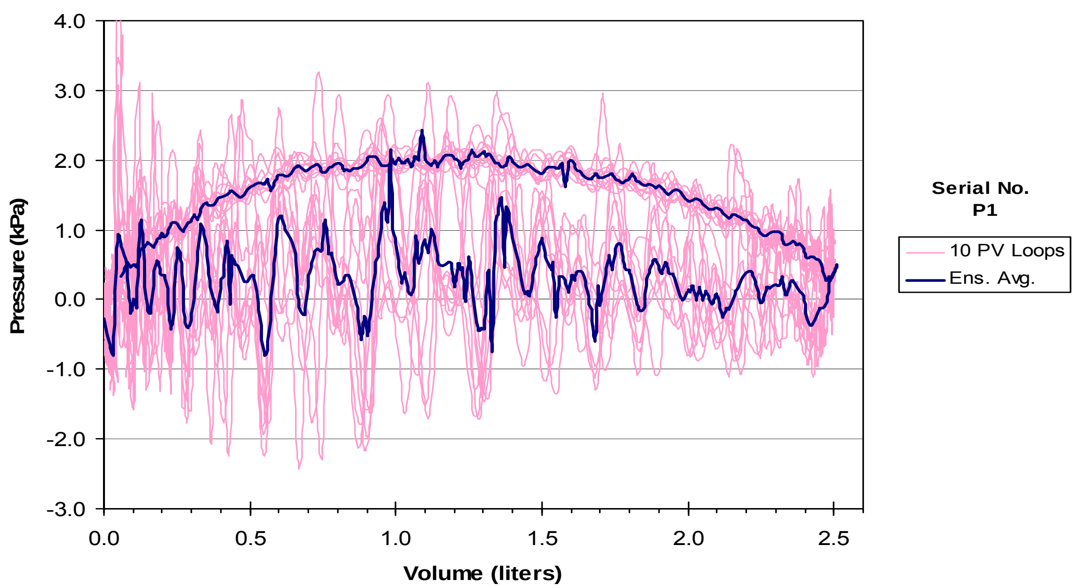

Figure 9. Pressure-Volume Loop for the Poseidon Xstream Deep Mk3 at RMV 62.5 L/min, 38 °F, and 198 fsw

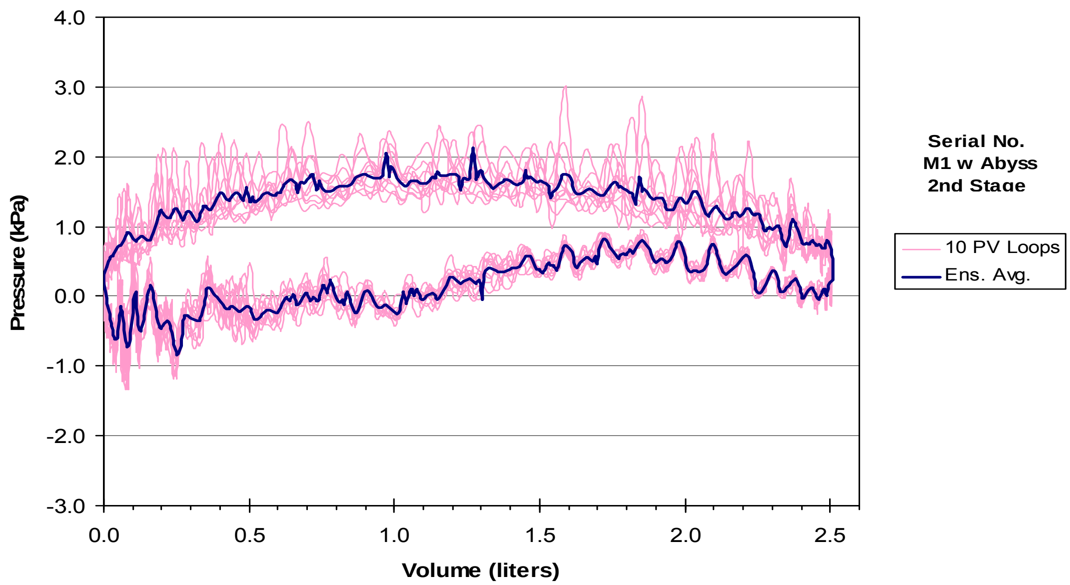

Figure 10. Pressure-Volume Loop for the Mares Proton Ice Extreme V32 with Abyss Second Stage at 62.5 L/min, 38 °F, and 198 fsw

Figure 11. Typical First-Stage Icing (Mares Abyss attached to tank Manifold shown with intermediate pressure sensor adaptor and hose attached for testing)

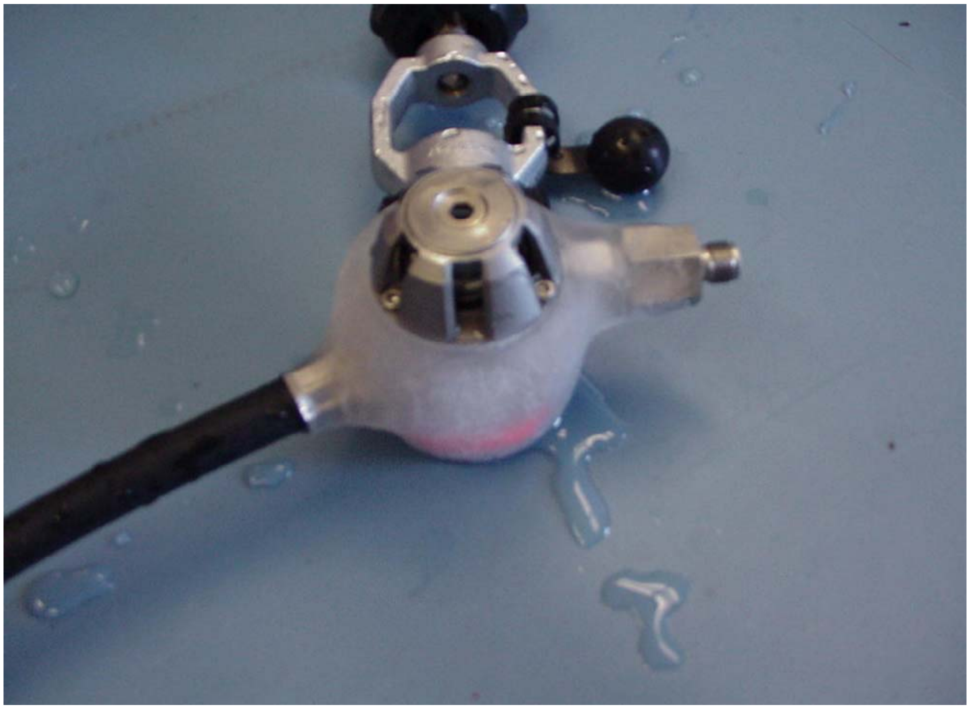
Figure 12. Typical First-Stage Icing (Poseidon Xstream Deep Mk3 with side-mounted first-stage shown with intermediate pressure sensor adaptor attached for testing)

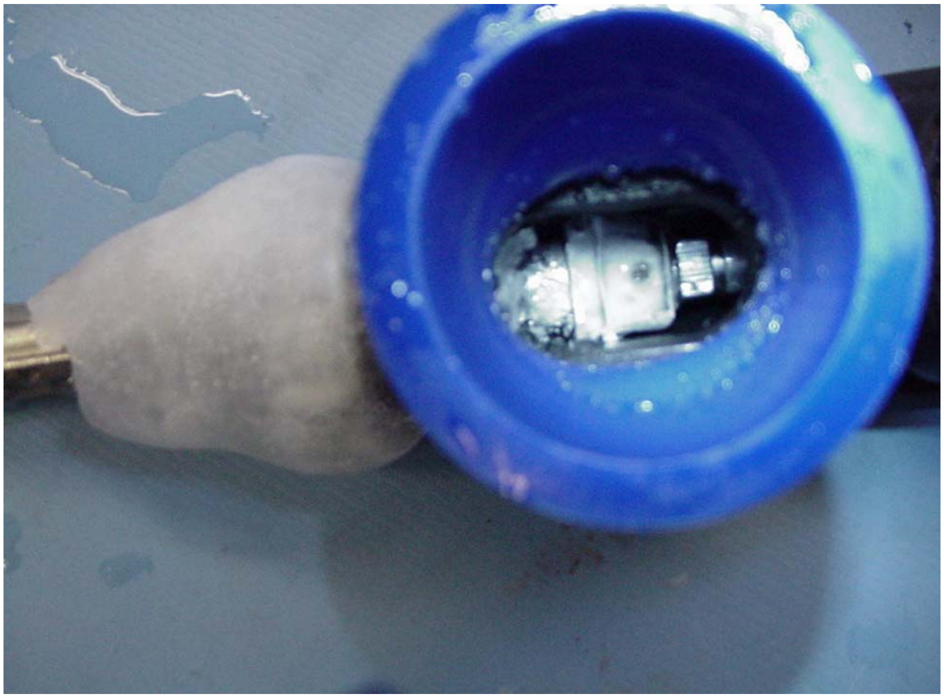

Figure 13. Typical Second-Stage Internal and External Icing (Poseidon Xstream Deep Mk3, side-mounted first stage shown with blue mouthpiece adaptor installed for testing)

DISCUSSION

Balanced, two-stage scuba regulators use pneumatic amplification to achieve the low inhalation efforts desired. The effect of pneumatic amplification on the inhalation resistive effort can be observed in the pressure-volume relationship of figures 8-10. After providing the initial inhalation cracking pressure, the resistive effort is nearly zero. Undulations (chatter) seen in the pressure-volume relationship during inhalation are caused by the non-compliance of the testing apparatus and are expected. The second-stage assembly of a regulator includes: (a) a main flow valve consisting of a movable poppet within a valve housing located inside the regulator body; (b) a seat, or a pilot valve, mounted within and carried by the main valve poppet; and (c) a pressure sensing diaphragm linked to the poppet. The mechanisms in which a second-stage free flow is manifested are thought to be the combination of the adiabatic cooling during the reduction of high-pressure supply air to intermediate pressures for subsequent gas transfer to the second-stage assembly — or the moist gas exhaled by the diver through the second-stage exhaust valve or reverse leakage of the exhaust valve around the seat during inhalation, either of which causing ice to precipitate around the exhaust valve and providing a path for gas flow. Loss of intermediate pressure control, and leakage of 2nd stage exhaust valves have also been seen to lead to free flow induced by icing.

In second-stage assemblies designed with a poppet-and-seat–style mechanism to control air flow, ice can build around the demand lever or the poppet-and-seat assembly

and eventually prevent both movement of the poppet and subsequent contact between the poppet and seat. Regulator models with second-stage assembly designs such as those of the Poseidon Xstream Deep Mk3 use the poppet combined with a pilot valve mechanism to control gas flow. These designs appear to be less susceptible to free flow due to ice buildup in cold water conditions.

Self-contained gas supplies are quickly depleted once a free flow is initiated. A sustained free flow does not prevent a diver from drawing a breath but does increase his exhalation resistive effort, as he tries to overcome the increased pneumatic amplification of the free flow. Furthermore, as Antarctic exposure has shown, divers under polar conditions have experienced free flow causing painful chilling of the mouth and teeth.[10] Once ice continues to build induced by a free flow of gas in the second-stage assembly, little can be done — short of shutting off the air supply or immersion in warmer waters — to stop the free flow. If ice built inside the second stage assembly should dislodge during an inhalation effort, it could create an obstruction to the flow of gas or initiate a pharyngeal reflex (gag reflex) in the diver.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the unmanned testing results under the test conditions and regulator configurations tested, the modified Mares Proton Ice Extreme V32 first-stage paired with a Mares Abyss second-stage configuration with attached IP hose — and the Poseidon Xstream Deep Mk3 model regulator in the side-mounted first-stage configuration — are recommended for use in water temperatures of 29 °F or higher. Furthermore, the Mares Proton Ice Extreme V32 first-stage regulator, with the cold water kit installed consisting of silicone oil and an environmental diaphragm, is recommended for use in water temperatures greater than or equal to 38 °F.

Any additional modifications — such as the elimination or substitution of any component, or the attachment of ancillary equipment (e.g., an octopus second stage, free-flow shutoff device/isolator, first-stage overpressure relief valve, or buoyancy inflation SPG or dry suit inflation devices) — to these regulator model configurations have not been tested by NEDU, and the performance of these regulators in cold water therefore cannot be predicted in such modified configurations. Furthermore, the standard regulator storage procedures of the U.S. Antarctica Diving Program were followed when practical: all test units were blown dry after their second-stage diaphragm covers had been removed but not rinsed — and the units were stored at dry room temperature (approximately 72 °F) between dives.[10] Before submersion, the regulators were not breathed, and the purge was not activated in an effort to avoid free-flow conditions. Regulator performance cannot be predicted if these *as-tested* usage and storage procedures are not followed.

No other regulators tested herein are recommended for cold water use; they should not undergo manned testing or currently be used under cold water conditions.

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GLOSSARY

ANU	approved for Navy use
COTS	commercial off-the-shelf
EDF	Experimental Diving Facility
fsw	feet of seawater
IP	intermediate pressure
kPa	kilo Pascal (force per unit area or pressure)
L/min	liters per minute
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
oronasal	pertaining to the mouth and nose
ppt	parts per thousand
psi	pounds per square inch (force per unit area or pressure)
PV	pressure and volume relationship
RMV	respiratory minute volume
SPG	submersible pressure gauge
Teflon®	brand name of polytetrafluoroethylene (PTFE)
UBA	underwater breathing apparatus
$T_{expired}$	expired temperature in degrees Celsius
$T_{inspired}$	inspired temperature in degrees Celsius
°C	degrees Celsius
°F	degrees Fahrenheit

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APPENDIX A

NEDU
TEST UNIT CONFIGURATIONS

Mares Proton Ice Extreme:
NEDU Tracking Code: MI1-MI5
V32 first-stage yoke with Cold Water Kit (oil/diaphragm system) installed
30-inch rubber intermediate pressure hose as standard
No user adjustments

Mares Abyss Extreme:
NEDU Tracking Codes: MA1-MA5
MR22T first-stage yoke and Cold Water Kit (dry system) installed as standard
Abyss second stage with integrated 30-inch braided intermediate pressure hose as standard
No user adjustments

Mares Proton Ice Extreme First Stage with Abyss Second Stage:
NEDU Tracking Code: MI1-MI5
V32 first-stage yoke and Cold Water Kit (oil/diaphragm system) installed as standard
Abyss second stage with integrated 30-inch braided intermediate pressure hose as standard
No user adjustments

Poseidon Xstream Deep Mk3:
NEDU Tracking Code: P1-P5
First Stage: Xstream Deep, Side-mounted DIN with yoke adaptor, Unit Number: 0100-000
2.3ft (0.70m) rubber intermediate pressure hose as standard
Second Stage: Xstream Deep, Black colored indicative of Deep model, Unit Number: 0120-000
(NOT TESTED: other Xstream models having various colored second stages as standard, including the models: Deco (white), Dive (gray), Duration (green) and Octopus (yellow)
No user adjustments

Sherwood Blizzard:
NEDU Tracking Code: SB1-SBI5
Model Number: SRB7900CE
First-stage yoke
32-inch rubber intermediate pressure hose as standard
Low profile exhaust Tee (Regulator as received included an additional larger exhaust Tee/bubble deflector but was not tested)
No user adjustments

Sherwood Maximus:
NEDU Tracking Code: SM1-SM5
Model Number: SRB7600CE
First-stage yoke
41-inch rubber intermediate pressure hose as standard
Low profile exhaust Tee (Regulator as received included an additional larger exhaust Tee/bubble deflector but was not tested)
User adjustments:
- Second-stage orifice set at midrange of travel
- Venturi assist set to left of mouthpiece as observed from mouthpiece

Figure A1. Mares Proton Ice Extreme V32 Regulator with Cold Water Kit

Figure A2. Mares MR22T First-Stage Regulator with Abyss Second Stage and Integrated Intermediate Pressure Hose

Figure A3. Modified Mares Proton Ice Extreme V32 Regulator with Cold Water Kit and Abyss Second Stage

Figure A4. Poseidon Xstream Deep Mk3 Regulator with Side-Mounted First Stage

Figure A5. Sherwood Blizzard Regulator with Low-Profile Exhaust Tee Attached

Figure A6. Sherwood Maximus Regulator with Low-Profile Exhaust Tee Attached

APPENDIX B

NEDU
TEST ARTICLE TRACKING NUMBERS

NEDU CODE	1st Stage Serial	Intermediate Pressure	2nd Stage Serial
Mares Proton Ice Extreme V32 First Stage with Cold Water Kit (Oil System)			
MI1	IE13133	130–136 psi	IE13133
MI2	IE13137	130–136 psi	IE13137
MI3	IE13135	130–136 psi	IE13135
MI4	IE13136	130–136 psi	IE13136
MI5	IE13138	130–136 psi	IE13138
Mares Abyss Extreme MR42 First Stage with Cold Water Kit (Dry System)			
MA1	AZ11923	130–136 psi	AZ11923
MA2	AZ12502	130–136 psi	AZ12502
MA3	AZ11924	130–136 psi	AZ11924
MA4	AZ12501	130–136 psi	AZ12501
MA5	AZ11922	130–136 psi	AZ11922
Poseidon Xstream Deep Mk3 (Side-Mounted First Stage)			
P1	0100-000900223	109–138 psi 123 psi Nominal	N/A
P2	0100-000900222	109–138 psi 123 psi Nominal	N/A
P3	0100-000900221	109–138 psi 123 psi Nominal	N/A
P4	0100-000900220	109–138 psi 123 psi Nominal	N/A
P5	0100-000900219	109–138 psi 123 psi Nominal	N/A
Sherwood Blizzard SRB7900CE			
SB1	7ER003990	120–150 psi	7ER003990
SB2	7ER003978	120–150 psi	7ER003978
SB3	7ER003989	120–150 psi	7ER003989
SB4	7ER003976	120–150 psi	7ER003976
SB5	7ER003977	120–150 psi	7ER003977
Sherwood Maximus SRB7600CE			
SM1	7EK004490	135–150 psi	7EK004490
SM2	7EK004495	135–150 psi	7EK004495
SM3	7EK004496	135–150 psi	7EK004496
SM4	7EK004497	135–150 psi	7EK004497
SM5	7EK004491	135–150 psi	7EK004491

APPENDIX C

NEDU
REGULATOR TESTING OUTCOMES

Model	Results
Phase 1	
Bench Test	
Mares	
Proton Ice Extreme V32:	Advanced to Phase 2
Proton Ice Extreme V32 w Abyss 2nd stage:	Advanced to Phase 2
Poseidon	
Xstream Deep Mk3:	Advanced to Phase 2
Sherwood	
Blizzard:	Advanced to Phase 2
Maximus:	Advanced to Phase 2
Phase 2	
Freeze-up Test	
Mares	
Proton Ice Extreme V32:	
198 fsw, 29 °F	Terminated
38 °F	Advanced to Phase 3
132 fsw, 29 °F	Terminated
Proton Ice Extreme V32 1st stage w Abyss 2nd stage:	
198 fsw, 29 °F	Advanced to Phase 3
Poseidon	
Xstream Deep Mk3: 198 fsw, 29 °F	Advanced to Phase 3
Sherwood 198 fsw, 29 °F	
Blizzard:	Terminated
Maximus::	Terminated
Phase 3	
Resistive Effort	
Mares	
Proton Ice Extreme V32:	Tested
Proton Ice Extreme V32 1st stage w Abyss 2nd stage:	Tested
Poseidon	
Xstream Deep Mk3:	Tested
Sherwood	
Blizzard:	Terminated in Phase 2
Maximus:	Terminated in Phase 2